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VISUALIZATION OF HIGH LATITUDE ION UPFLOW IN SUPPORT OF THE IMAGE MISSION

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Introduction

The study of the magnetosphere is a 400 year old science that began with the publication by Gilbert, in 1600, of his hypotheses that the Earth was a giant magnet. Since then we have learned many things about the magnetosphere, particularly in the last 40 years of the space age, but we still have many unanswered questions. In spite of the many thousands of observations of this system we still lack a global understanding of how it works. This is due to its large size and tenuous nature that mean that any measurement made of the fields or particles involved only give one a knowledge of the local conditions at a given time. To gain a global perspective through such observations would require the simultaneous operation of thousands of satellites spread throughout the magnetospheric system in addition to observations made on the ground. Such a program would be impractical at least from financial considerations. What is needed for the advancement of magnetospheric physics is to develop the same capabilities that astrophysicists, solar physicists and meteorologists have been using for years --- the ability to stand back from the object under study and see it in its entirety.

The challenge for doing this for the magnetosphere is that the particle densities are very low and the material is, for the most part, not luminous. In the last 25 years several ideas have been proposed that would allow at least the imaging of certain portions of the magnetosphere. These include imaging of the plasmasphere through the resonant scattering of solar 304 A from He^+ ions, imaging of various hot plasma populations (i.e. the ring current, plasmasheet, upflowing ionospheric ions, etc.) from the neutral atoms that result when ions of these populations charge exchange with the hydrogen geocorona, and imaging the aurora at various wavelengths in the far ultraviolet. In addition a novel technique for probing various boundaries in the magnetosphere by bouncing low frequency radio waves off of them has been extensively studied. Such a technique is analogous to the way the under water world can be probed with sonar.

About five years ago NASA convened a science working group to study the possibility of flying a magnetospheric imaging mission. This resulted in a number of proposals for such a mission, one of which was selected to be the first MIDEX mission, to be launched in early 2000. The mission is called IMAGE (Imager for Magnetopause to Aurora Global Exploration) and its P.I. is J. Burch at SwRI. The IMAGE spacecraft will carry imagers to view the plasmasphere, aurora, ring current, inner plasmasheet, and upflowing ionospheric ions as well as a radio sounder to probe the location, shape and dynamics of the magnetopause, plasmapause, etc. Between its selection last April and the non advocacy mission review, which takes place next spring, the IMAGE teams needs to further refine the design of the mission and its instruments. The theory and modeling (T&M) subgroup of this team has the task of demonstrating what kind of images the instruments on IMAGE will see as well as showing that useful scientific information can be extracted from such images.

As a central element to the efforts of the T&M subgroup we have decided to simulate and create synthetic images for the magnetic cloud event of October, 1995. In

this event a large cloud, with high plasma densities and strong magnetic fields, ejected from the sun collided with the earth's magnetosphere triggering a three day period of intense magnetic storms and substorms. This event was observed from a number of different spacecraft and on the ground so we have a good data set to work with. In our work we will place the IMAGE spacecraft in the magnetosphere on its proposed orbit, with its proposed instruments, to see what it would see had it been there. Existing models of the plasmasphere, ring current and magnetopause will be run for this event to give the structures for the imaging instruments. There are several models which are lacking and which need to be developed. These include a model for the cusp, the inner plasmasheet and the upflowing ions. My task this summer was to develop the upflowing ion model and use it to create synthetic images.

The Model

O^+ and H^+ ions in the ionosphere typically have low energies, often less than one eV. The LENA (Low Energy Neutral Atom) imager will have a low energy cutoff of 10 eV and will not be able to see such ions unless they are energized up into the range of 10--300 eV. This happens frequently in the auroral zone and cusp regions in the ionosphere where energy, in the form of precipitating energetic electrons, ions and currents, is deposited by various processes in the magnetosphere. The amount of ions flowing out is dependent on the amount of energy flowing in and both go up as magnetic activity increases. In the model that I developed the first task was to define the source function.

For this function I assume that all energized ionospheric ions are launched from an altitude of 1000 km. At that altitude the velocity distribution of these ions is assumed to be bi-Maxwellian with a perpendicular temperature 10 time larger than the parallel temperature. This is equivalent to assuming that all of the ions are energized by waves (ion cyclotron or lower hybrid) whose k vectors are nearly perpendicular to **B**. Next I assume that the upward ion flux in the auroral zone and polar cap is proportional to the downward energy flux of the precipitating auroral electrons. The pattern for this flux was taken from the model of Hardy et al. (1987). In the auroral zone at the 1000 km boundary, I assume that the upflowing ions have a perpendicular temperature of 300 eV. In the polar cap this value is 50 eV and in the cleft ion fountain the value used is 10 eV. The total ion flux from the auroral zone and polar cap is taken to be that given by the expressions obtained by Yau et al. (1988) based on 6 years of EICS data from DE 1. These expressions are

$$F\,(O^+) = 10^{25} \exp[0.01\,(F_{10.7}-100)]\,\exp(0.5\,Kp) \text{ ions/s}$$

$$F\,(H^+) = 2.5 \times 10^{25} \exp[-0.0027\,(F_{10.7}-100)]\,\exp(0.23\,Kp) \text{ ions/s}$$

where Kp is an index which measures magnetic activity and $F_{10.7}$ is an index which measures the EUV output of the sun. For the cleft ion fountain the total O^+ flux was assumed to have a constant value of 10^{25} ions/s and the H^+ flux had a value of 2.5 X

10^{24} ions/s. The location and size of the cleft ion fountain was taken from the De 1 observations as reported by Giles et al. (1994) and Pollock et al. (1990).

Once ions leave the lower boundary at 1000 km they flow upward along the magnetic field lines and drift across these field lines. Throughout the region which I modeled (above 50^{o} magnetic latitude and out to a geocentric distance of 5 R_E) I assumed that the magnetic field was dipolar. I also assumed that the electric field was only perpendicular to the magnetic field. As a result ions will drift across the magnetic field due to the curvature, gradient and **E** X **B** drifts, all of which were included in the particle equations of motion. The equations of motion used in the model were the guiding center equations as developed by Delcourt et al. (1988). Since I assume that **B** field lines are equal potentials (no **E** parallel) the electric field throughout the volume of interest is defined by the electric potential in the ionosphere. In the current version of the model the Volland (1978) model for this potential is used. Later versions will be updated to the Heppnard Maynard model used in the Rice convection model.

The code which implements this model does the following. The ionosphere at 1000 km is subdivided into about 1000 small regions within which the upflux of H+ and O+ ions is assumed constant. From each of these regions 20 ions, whose initial energies and pitch angles are chosen from the assumed velocity distribution , are launched and followed until they leave the region. At each step along the way their energy and pitch angle are found and a 5 dimensional array, which contains the ion flux as a function of position, pitch angle and energy, is updated. The process of updating this array is continued until all particles from all regions have been launched and tracked through the simulation region. Since the particles are not all followed simultaneously, or on the same time step, the solution found is a steady state solution.

Once the five dimensional ion flux function has been found for both H^+ and O^+ it is converted into an ENA flux function for neutral H and O. The reactions which produce this results are

$$O^+ + H = O + H^+ \qquad \text{cross section} = 1.5 \times 10^{-15}\ \text{cm}^2$$

$$H^+ + H = H + H^+ \qquad \text{cross section} = 3.0 \times 10^{-15}\ \text{cm}^2$$

In these reactions there is very little energy exchange between the ion and the hydrogen atom so that the velocity distribution of the ions is directly translated into the velocity distribution of the neutral atoms. The neutral hydrogen with which the ions react is part of the earth's geocorona. The production rate of the energetic neutrals will therefore decrease as one moves away from the earth because of the decreasing density of the hydrogen. The model for this density function used in this work is that of Rairden et al. (1986).

Once the ENA flux function is available it is possible to create images of this flux by using a line-of-sight integration code since the medium is very tenuous and one can see

all the way through it. The code used was one developed by D. L. Gallagher here at MSFC. To run the code one gives it a luminosity flux function, in the form of a subroutine, the position of the spacecraft, its viewing direction and characteristics of the camera such as angular resolution, effective area and field of view. The code returns a sky map of the flux into the instrument for each pixel bin.

Images of Upflowing Ions

Figure 1 is a sequence of images of the outflowing H+ ions whose energies lie between 128 eV and 300 eV (high energy channel of the LENA instrument). The numbers with each image are the times, in UT, when the image was made. These times correspond to an interval near the most intense part of the magnetic storm triggered by the October 1995 magnetic cloud event when the IMAGE spacecraft is approaching perigee from the northern hemisphere. The intensity scale is an inverted gray scale where black represents the most intense fluxes and white the least intense. The black circle in each figure is an outline of the earth while the small plus sign indicates the direction toward the north magnetic pole.

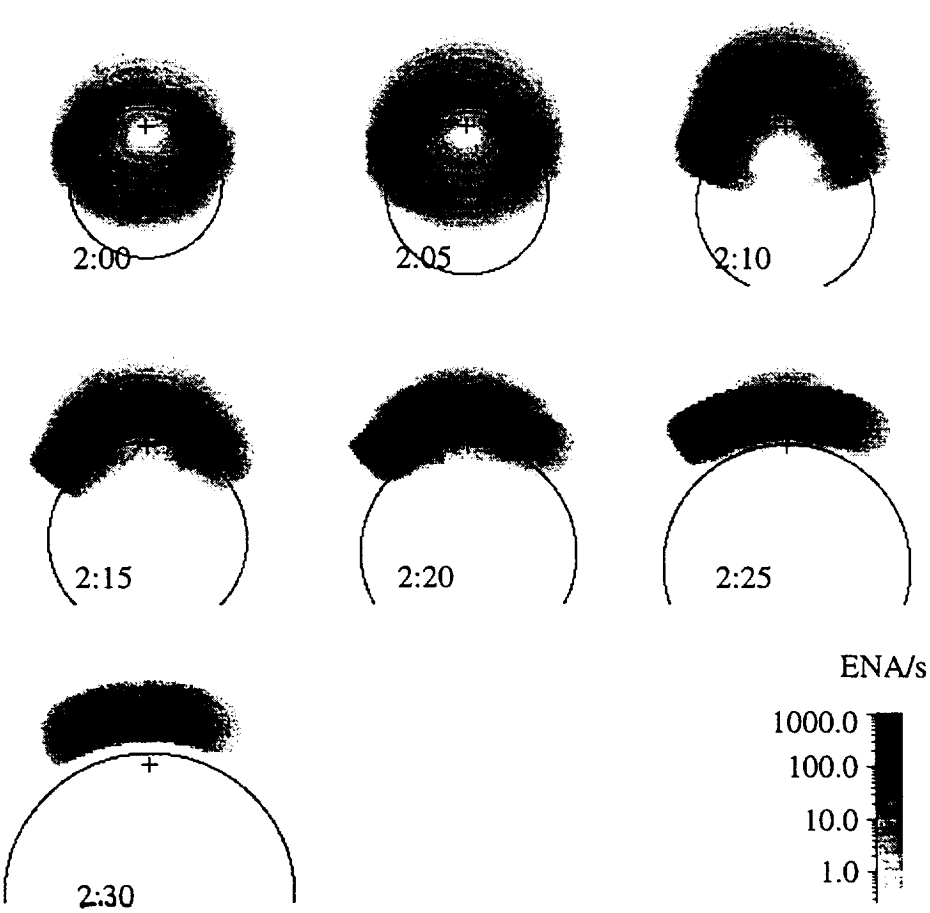

Figure 1. A sequence of H^+ ENA images from a time period during the most intense portion of the magnetic storm.

For this time interval the Kp is about 7 and $F_{10.7}$ is about 80. The H^+ flux from the auroral zone and polar cap is 1.3 X 10^{26} ions/s and from the cleft ion fountain is 2.5 X 10^{24} ions/s. The corresponding O^+ fluxes are 2.7 X 10^{26} ions/s and 10^{25} ions/s respectively. Although the auroral zone fluxes dominate the cleft ion fountain it is possible to see this source in the lowest energy channel (10-23 eV).

One of the things that the sequence of images in figure 1 demonstrates is that during intervals when the IMAGE spacecraft is passing close to the earth and the direction from which it is viewing the upflowing ions is changing rapidly it may be possible to use tomographic techniques to reconstruct the ion flux function from the images. In a single image the pitch angle distribution of the ions at a given point on a given field line is sampled at only one pitch angle. This same field line is also sampled at other pitch angles at other locations. (The pitch angle sampled is determined by the angle between the look direction and the magnetic field.) It may be possible to fill in the total pitch angle distribution at all points along the field line by adiabatically mapping the observed flux at one point to other points along the field line. If only one field line were emitting ENA than a complete reconstruction of the pitch angle distribution along the whole field line would be possible with a single image. Because the counts in a single pixel would, in general, not come from a single field line a sequence of images, taken from different vantage points, would be needed as a minimum to sort out what comes from a given field line.

It is clear that much work with these images needs to be done.

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